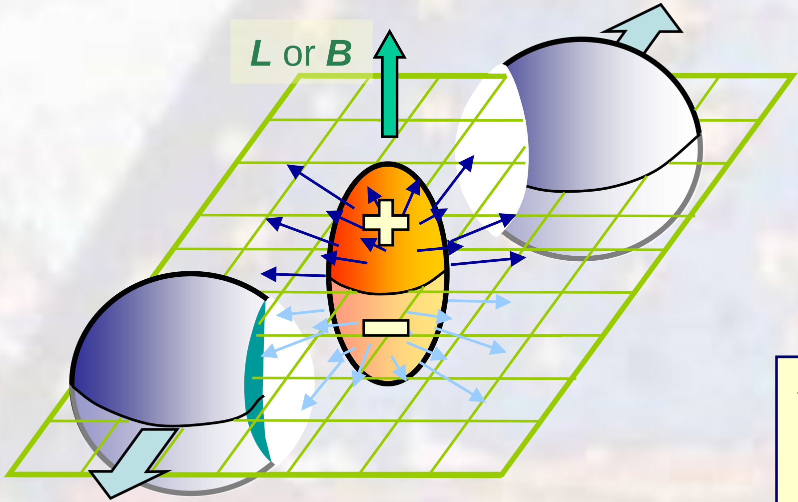
Probe for the spontaneous strong parity violation in heavy ion collisions at RHIC.

Status and outlook.

Sergei A. Voloshin

Wayne State University, Detroit, Michigan



Looking for the (P-odd) effect of charge separation along the system orbital angular momentum, (*D. Kharzeev*, hep-ph/0406125. Phys.Lett.B 633 (2006) 260.)

STAR Parity-v Group:

Indiana: I. Selyuzhenkov
BNL: V. Dzhordzhadze, R. Longacre, Y. Semertzidis, P. Sorensen
LBL: J. Thomas
Yale: J. Sandweiss, E. Finch, A. Chikanian, R. Majka
UCLA: G. Wang, D. Gangadharan
Wayne State: S. Voloshin

Synopsis of this talk

•P-violating effects, including charge separation, is a must in QCD.
It is “intrinsic” to QCD, e.g. being the basis for the chiral symmetry breaking.

•Quantitative predictions are not advanced and, from my point of view, are good to the order of magnitude. They predict asymmetry ~10^{-2}, that is within reach of the experiment.

•Using an observable that is directly sensitive to the charge asymmetry, STAR detects a signal that is in rough qualitative agreement with theoretical predictions.

•Numerous tests for the detector/acceptance effects indicate that it is unlikely that the signal is faked by the detector.

•The observable is P-even and can be generated by physical effects not related to the strong parity violation. Some of those (which can be clearly identified, e.g. “flowing” resonances) can be reliably eliminated from the list. Tested event generators do not reproduce the signal (magnitude and often charge combination dependence), but note that at present, neither event generator can describe even “simpler” (in fact, almost any) correlations that are not necessarily related to P-odd effects.
(more in talk by J. Sandweiss)

•In view of the importance of the physics, a dedicated program aimed on study of non-perturbative QCD physics can be envisioned both on theoretical and experimental sides.

Outline:

1. The effect. Latest picture.
2. Observable
3. Results
4. Tests (“data driven”)
5. Detector effects (simulations) and physics background) – J.S.
5. Building a program?

Latest picture. "Predictions".

Qualitatively, the easiest way to imagine the picture is to have in mind
that in the presence of topologically non-trivial classical gluonic fields (instantons, sphalerons),
static magnetic field induces *parallel* electric field.
The direction of the induced electric field (parallel or antiparallel) depends on
the sign of the topological charge of the gluonic field configuration.

1. Preferential emission of the same charge particle along the system orbital momentum (magnetic field).
Oppositely charged particles get "kicks" in the opposite directions.

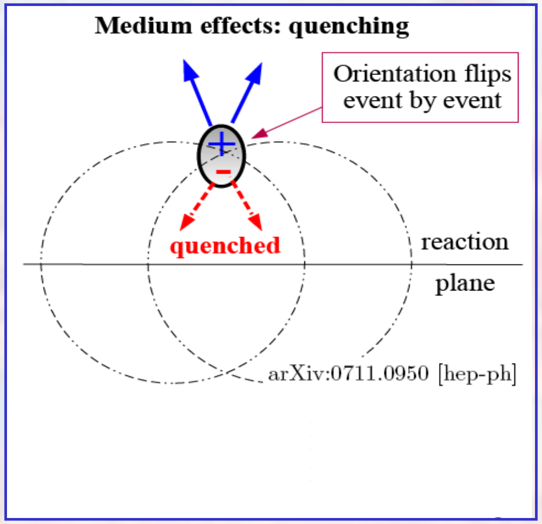
2. "Quenching" in the dense medium should lead to suppression of "back-to-back" (opposite charge) correlations. The suppression should be stronger in AuAu compared to CuCu, in central collisions compared to peripheral.

3. Effect is likely localized at pt <~ 1 GeV/c, though radial flow could move it to higher pt.

4. The effect should have a "typical" $\Delta\eta$ width of order ~ 1.

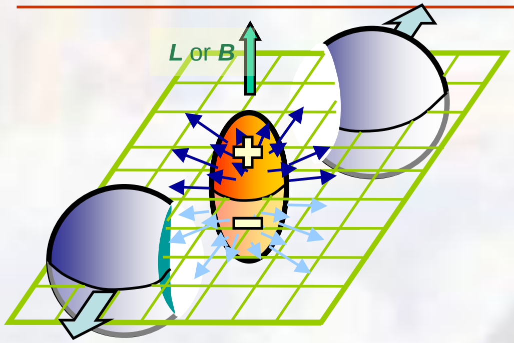
5. Asymmetry should be directly proportional to the strength of the magnetic field, i.e. ~Z.

6. Predictions for collision energy and atomic number dependencies are possible, but require more detailed calculations.



Observable

S.A. Voloshin, Phys. Rev. C 70 (2004) 057901



Particle distribution effectively can be described by:

$$\frac{dN_\pm}{d\phi} \propto \left(1 + 2v_1\cos(\Delta\phi) + 2v_2\cos(2\Delta\phi) + \ldots + \right.$$
$$\left. + \; 2a_\pm \sin(\Delta\phi)\right), \qquad (1)$$

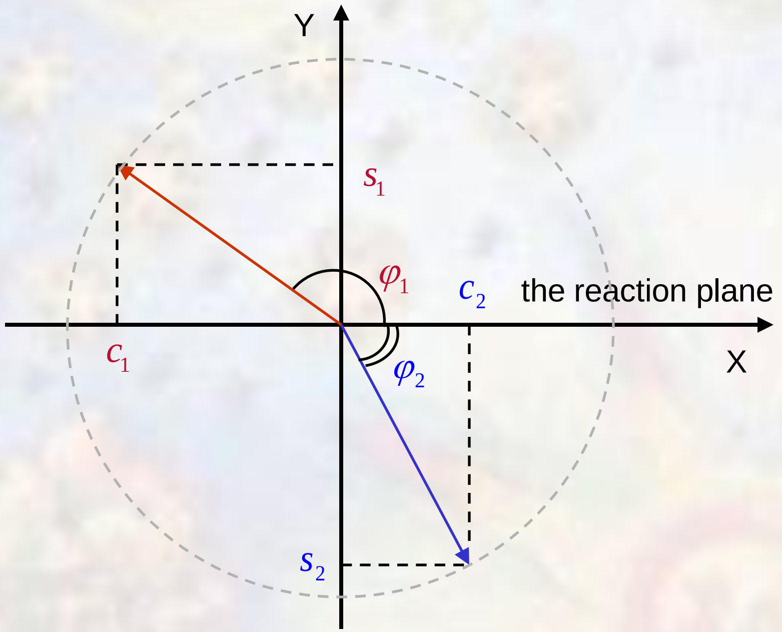
$$\Delta\phi = \phi - \Psi_{RP}$$

$a > 0$ ➔ preferential emission along the angular momentum,
$a_+ = -a_-$,
The sign of Q vary event to event➔ one has to measure correlations, $\langle a_\alpha a_\beta \rangle$, $\mathcal{P}$-even quantity (!)

$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle =$$
$$= \langle\cos(\phi_\alpha - \Psi_{RP})\cos(\phi_\beta - \Psi_{RP})\rangle - \langle\sin(\phi_\alpha - \Psi_{RP})\sin(\phi_\beta - \Psi_{RP})\rangle$$
$$\approx (v_{1,\alpha}v_{1,\beta} - a_\alpha a_\beta)$$

Use the third particle as a measure of the reaction plane

$$\langle\cos(\phi_a + \phi_\beta - 2\phi_c)\rangle = \langle\cos(\phi_a + \phi_\beta - 2\Psi_{RP})\rangle\, v_{2,c}$$



Average

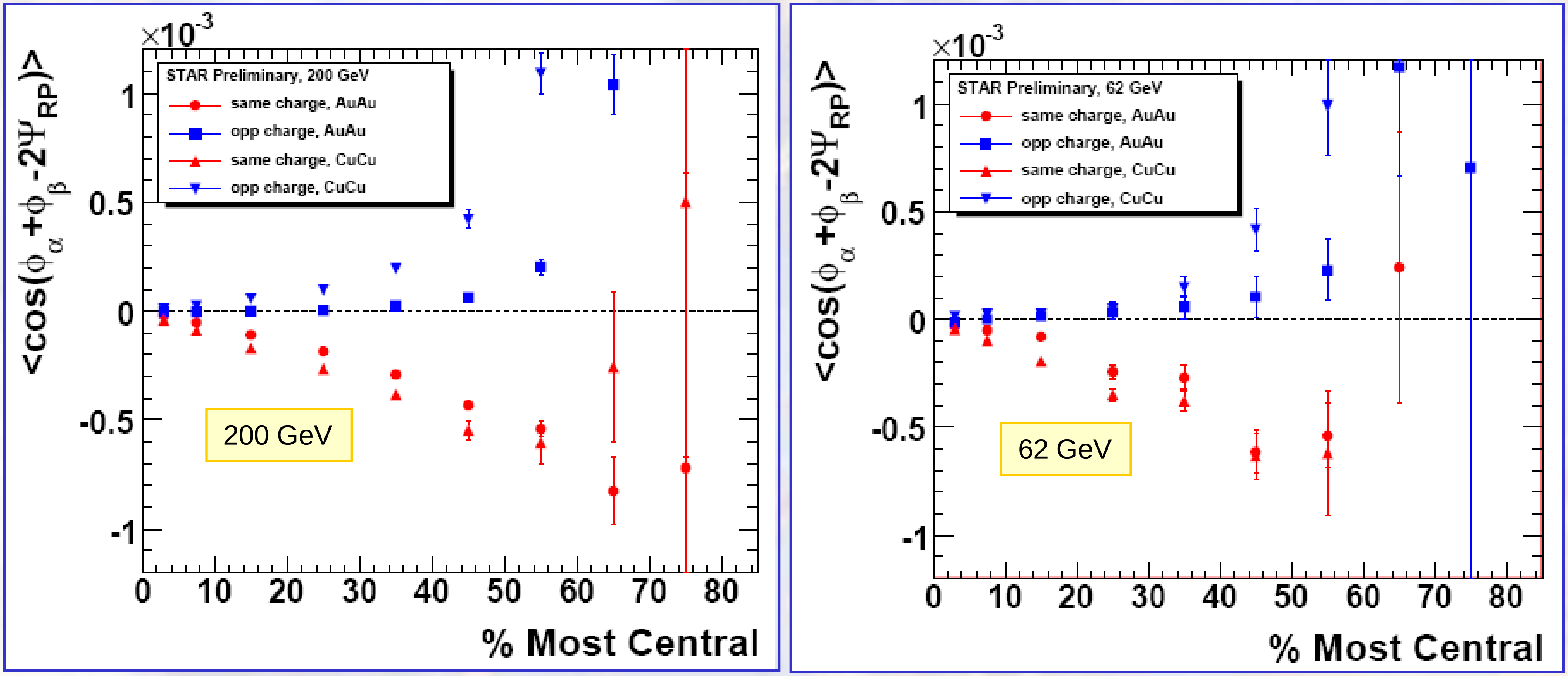
$$\langle\cos(\varphi_1 - \varphi_2)\rangle = \langle c_1c_2 + s_1s_2\rangle$$

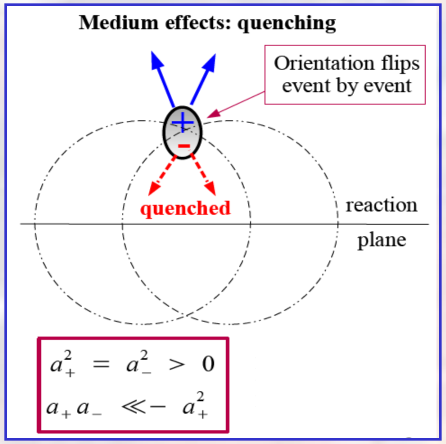
and modulations

$$\langle\cos(\varphi_1 + \varphi_2 - 2\Psi_{RP})\rangle = \langle c_1c_2 - s_1s_2\rangle$$

Has been verified using particle "c" from different detectors

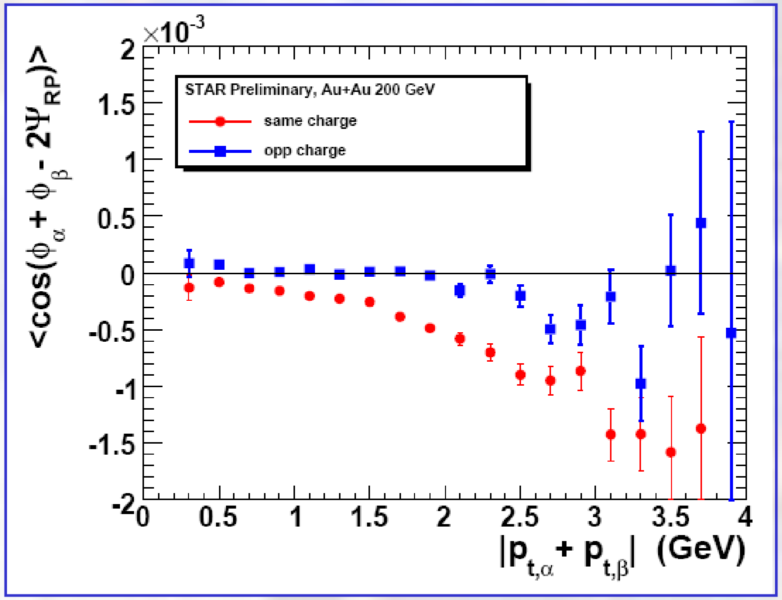
Results. Au+Au, Cu+Cu, 200 and 62 GeV.

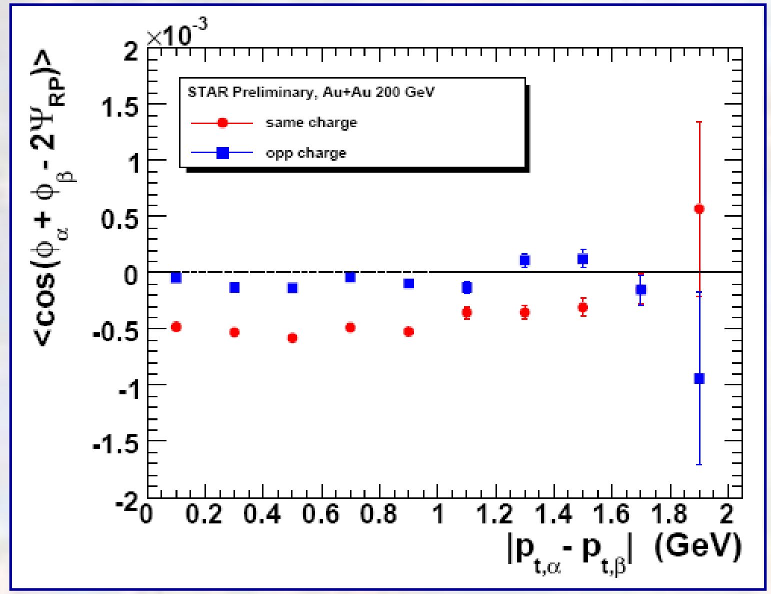




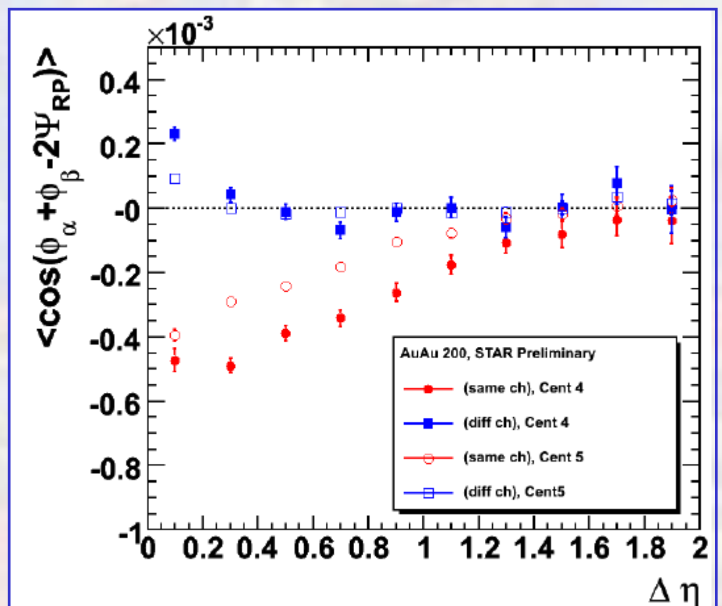
+/– signal in Cu+Cu is much better pronounced, qualitatively in agreement with “theory”.

Transverse momentum and Δη dependences (AuAu200).





The signal extends to too high pt's?



Typical "hadronic" width. Would be consistent with "theory"

Data driven tests/checks

What have been done/checked: (in red – check for detector effects)

1. Run2 – Run 4 comparison — quite different detector/beam settings!
2. Analyses of I. Selyuzhenkov, V. Dzhordzhadze, D. Gangadharan, A. Chikanian, J. Thomas, G. Wang, S. Voloshin agree on the signal.
3. Different field polarities
4. Event plane from particles of different charges
5. Event plane from TPC and FTPC

   (3–5: Acceptance effects, "recentering")

6. Particles 1 and 2 from different halves of TPC
7. Dependence on ZDC coincidence rate (luminosity)

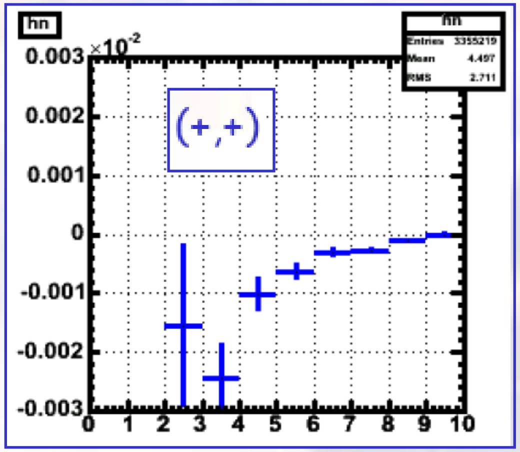
   (6–7: Space charge)

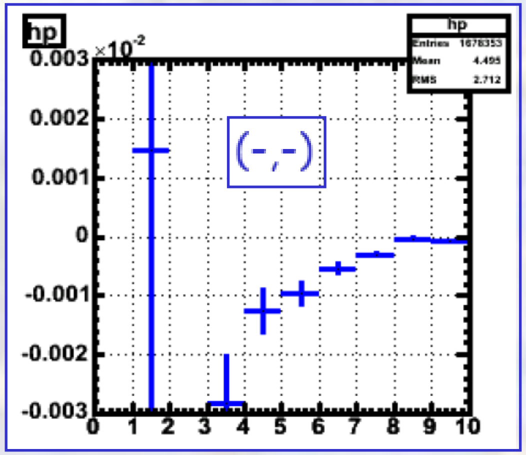
8. Dependence on vertex Z position
9. Cutting out electrons
10. Results obtained (qualitatively similar) for AuAu@200, AuAu@62, CuCu@200, and CuCu@62
11. *Global polarization* effect (which could contribute to the observable) have been measured (and found to be consistent with zero). Published.
12. Directed flow has been measured, ($v_1 \sim 10^{-3}$) published.

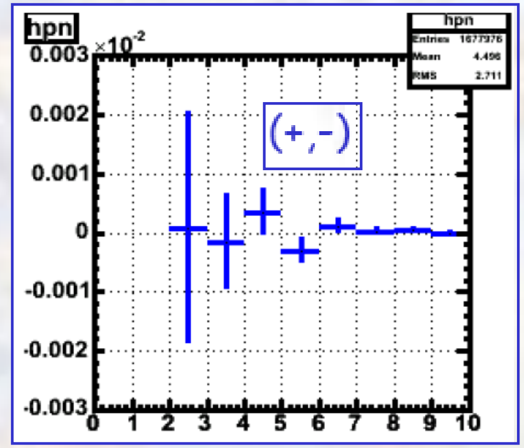
Comparison of Run2 with Run 4

$$\langle \cos(\varphi_a + \varphi_b - 2\varphi_c) \rangle = (v_{1,a} v_{1,b} - a_a a_b) v_{2,c}$$

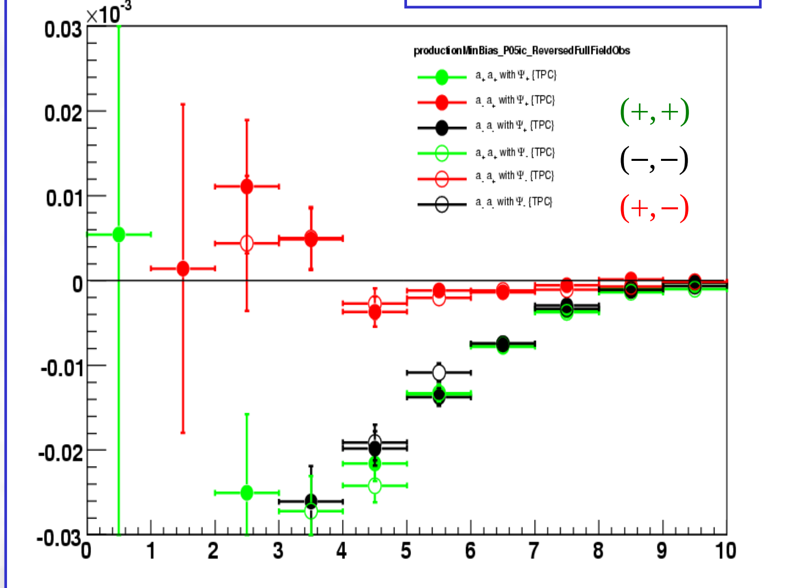
STAR Collaboration meeting July 12-17, 2004 *S.A. Voloshin*







Ilya Selyuzhenkov

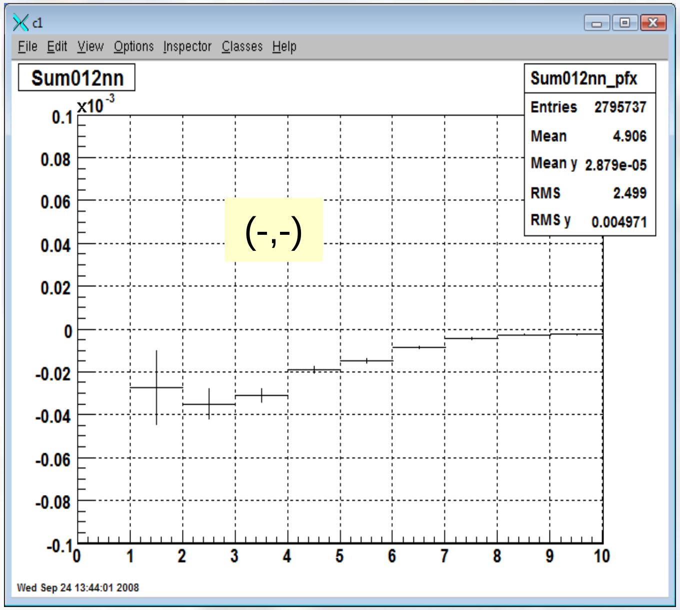


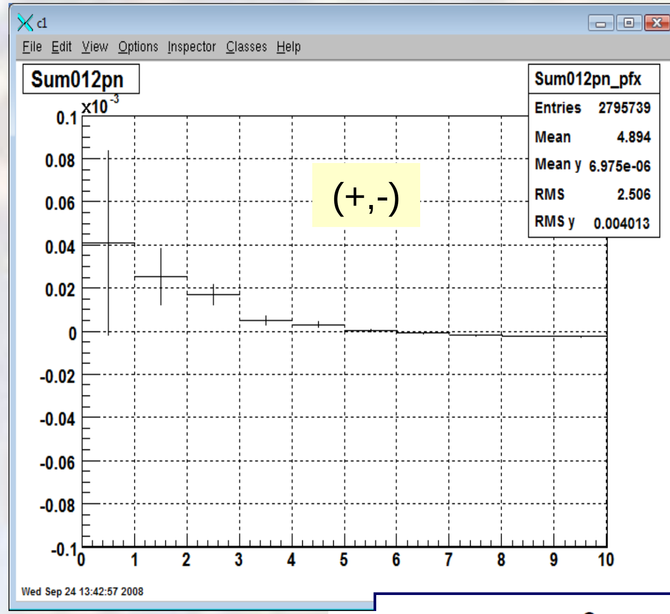
Note difference in average luminosity, space charge, etc.

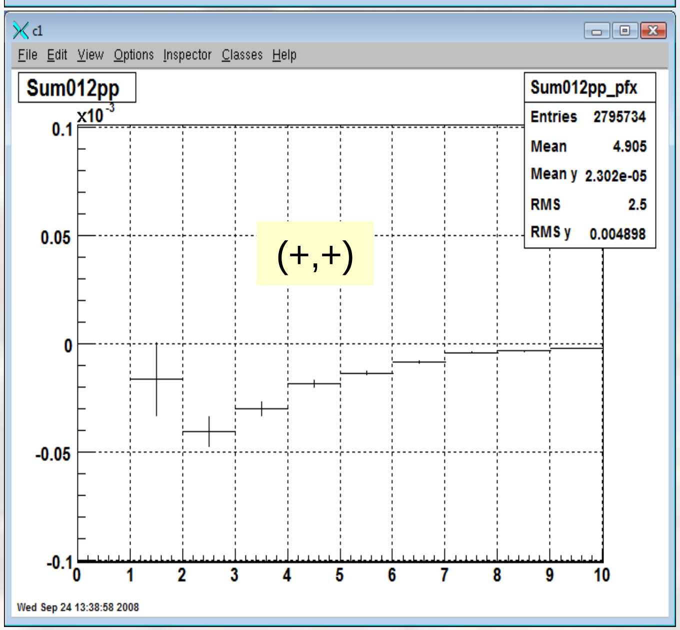
Very similar results

"Blind" analysis by J. Thomas

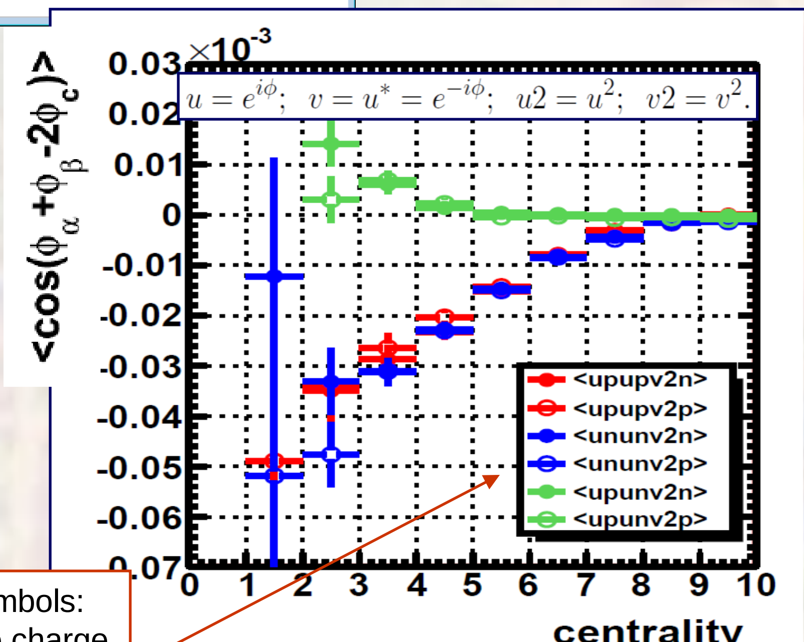
$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle$







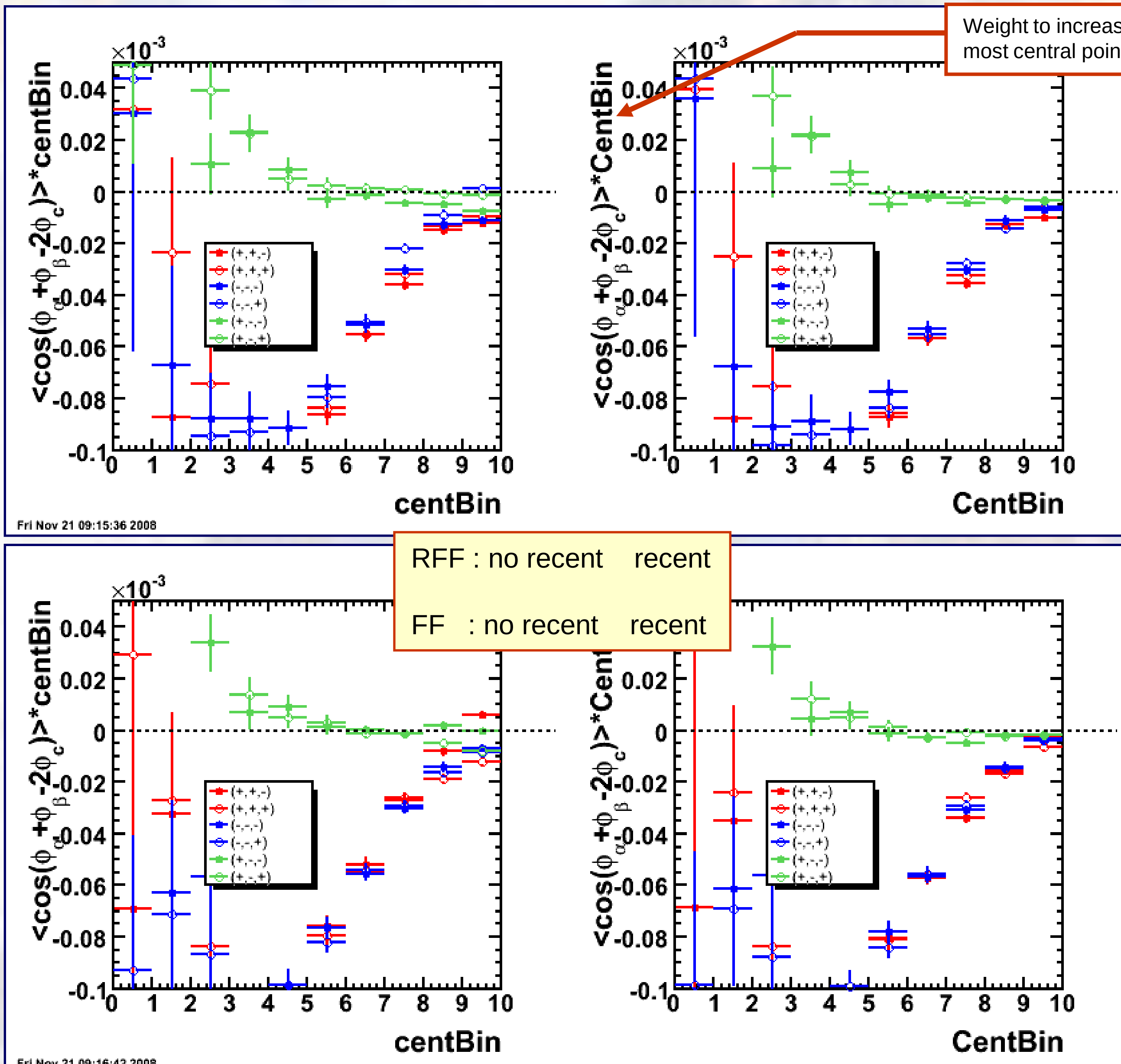
Compare to S.V.:



Open/filled symbols: depend on the charge of particle "c"

"Recentering" effect

Weight to increase visibility of most central points



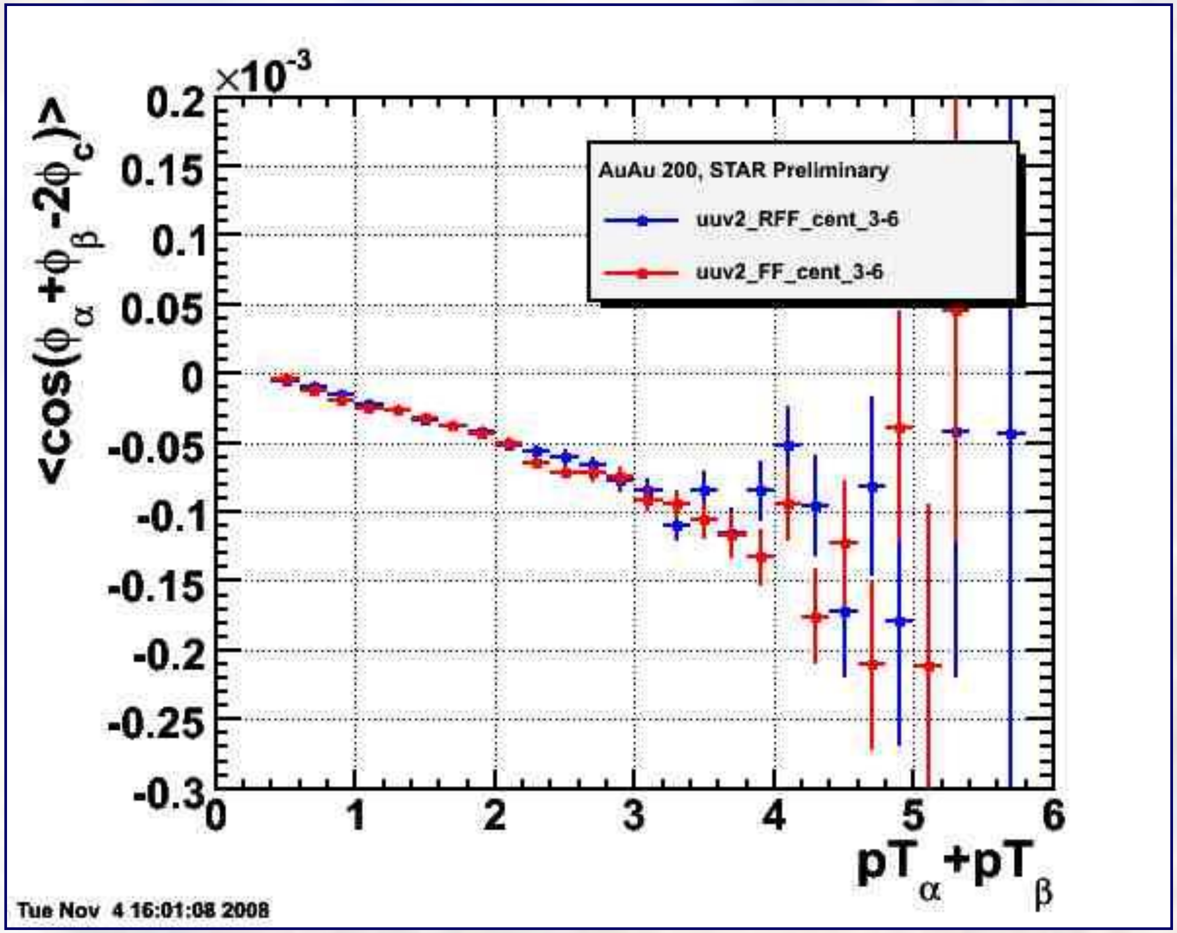
RFF : no recent recent

FF : no recent recent

Recentering is a method to correct for the acceptance effects (calculate cumulant). More on that in extra slides.
Acceptance effects are small for 3-particle correlator and somewhat larger for "average" correlation <cos(phi1-phi2)>.

Recentering is performed differentially on
RunID, RFF/FF,
Charge, Eta, Pt
VertexZ

pT dependence, FF vs RFF



How it is done:

1. Define pt bins in 0<pt<3 GeV
2. Correlate particles in diff. bins using unit weight for each bin, independent of number of particles in the bin.

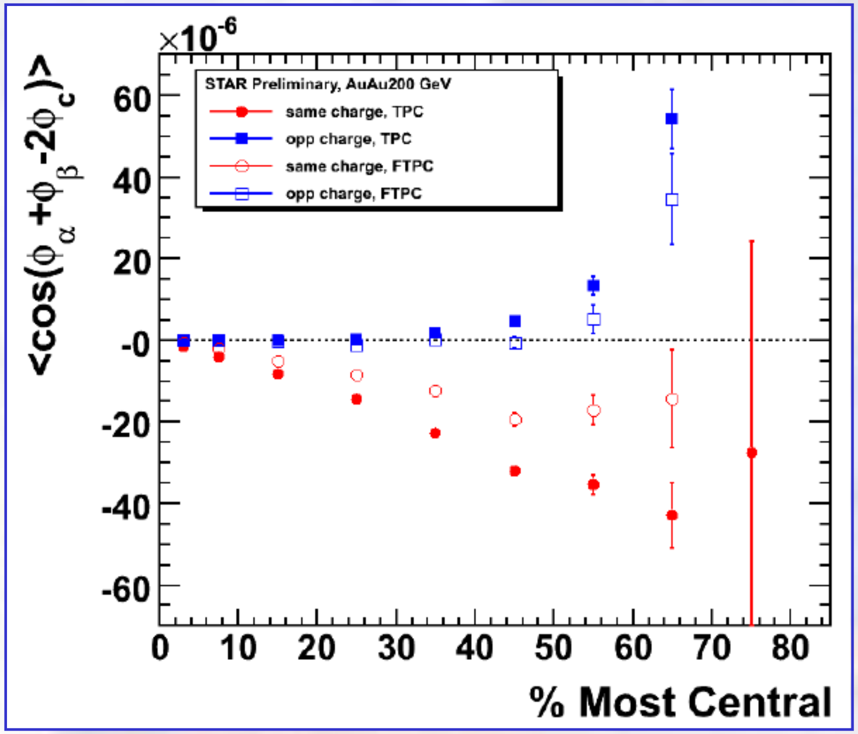
3 Both particles within eta region of width 1.

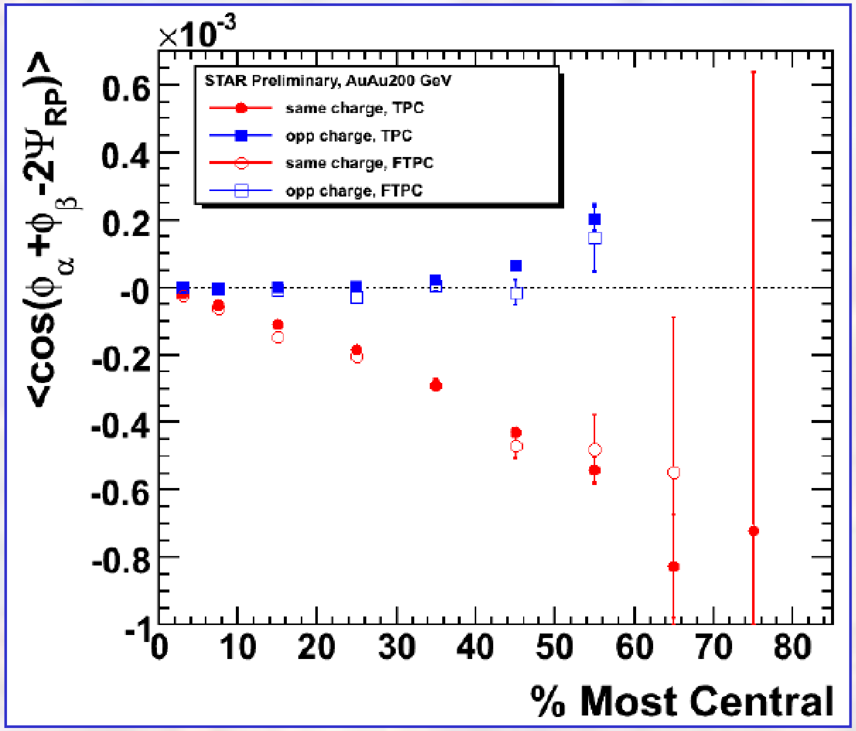
Dividing out RP resolution. (Reaction plane from TPC and FTPC)

Testing: $\langle\cos(\phi_a+\phi_\beta-2\phi_c)\rangle = \langle\cos(\phi_a+\phi_\beta-2\Psi_{RP})\rangle\, v_{2,c}$

$\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$

$\langle\cos(\phi_a+\phi_\beta-2\Psi_{RP})\rangle.$





Using ZDC-SMD for the (first harmonic) event plane yields similar agreement, though with larger uncertainties (G. Wang).

Where it could go?

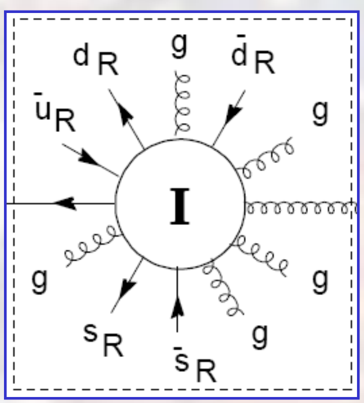
One could think on experiments / theoretical developments to prove or disprove a particular problem of the strong parity violation, but in principle one could envision a more general program to address non-perturbative QCD: vacuum, hadronization, etc.

The development will depend strongly on the theory. We need more of theoretical guidance and detailed calculations (at least where it looks quite possible: dependence on collision energy, centrality, system size, etc.)

To attract more people, both theorists and experimentalists, to this problem/program it is very important to start this discussion at major conferences.

A couple examples for the "program":

Identify other features of the "topological bubbles", and extend experimental search.
e.g. instanton "bubble" decay <u>isotropically</u>, it leads to <u>equal number of q-qbar pairs of all flavors</u>.
We can check this! (but how reliable such a prediction is? Is it possible to have only one u-ubar?)



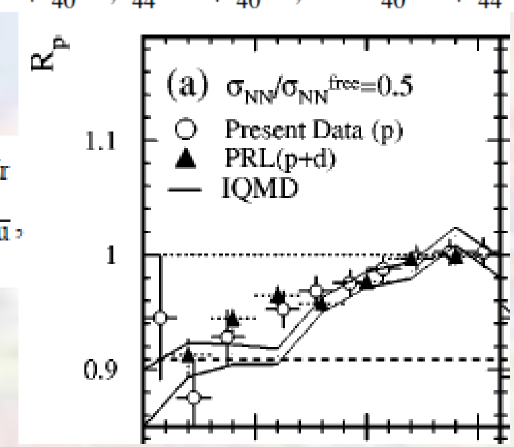
Instanton subprocess:
Δ chirality = 2 n_f

Colliding isobaric nuclei (the same mass number and different charge) and by that controlling magnetic field

GSI: FOPI Collabortion

$^{96}_{44}\mathrm{Ru}+^{96}_{44}\mathrm{Ru}$, $^{96}_{40}\mathrm{Zr}+^{96}_{40}\mathrm{Zr}$, $^{96}_{44}\mathrm{Ru}+^{96}_{40}\mathrm{Zr}$, and $^{96}_{40}\mathrm{Zr}+^{96}_{44}\mathrm{Ru}$

$$R_p=\frac{N_y^{\mathrm{Ru+Zr}}}{N_y^{\mathrm{Zr+Ru}}},$$

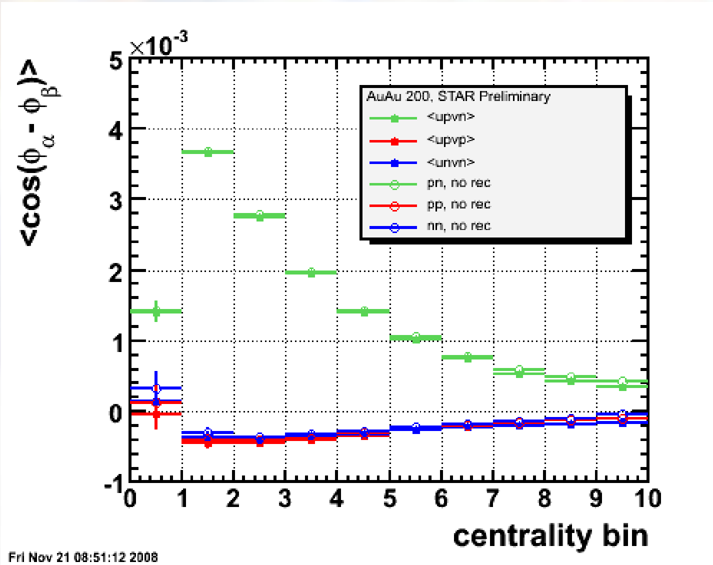


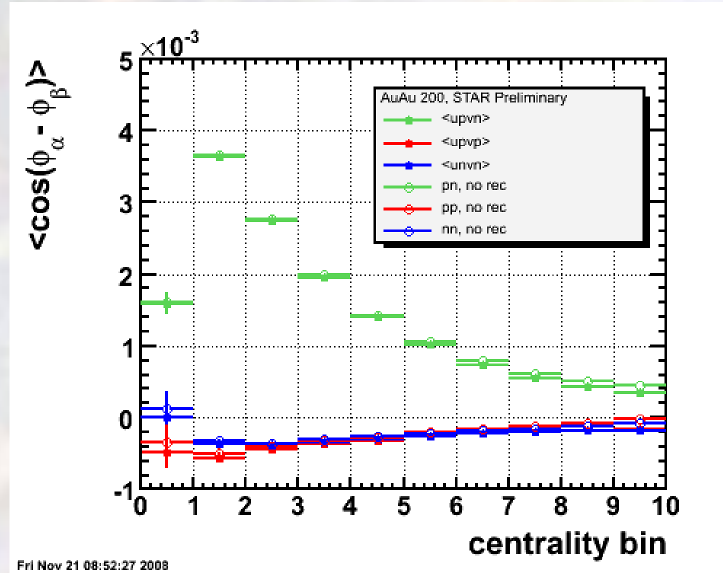
 17-December-2008, Parity BNL meeting. S.A. Voloshin

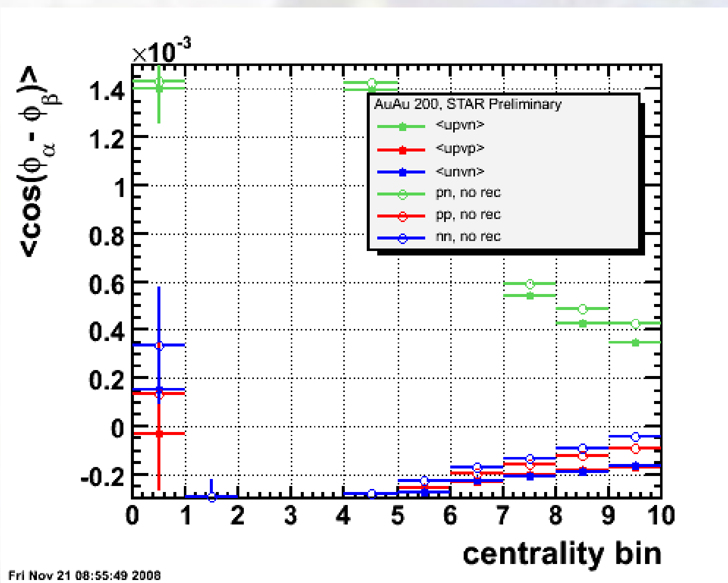
WAYNE STATE UNIVERSITY

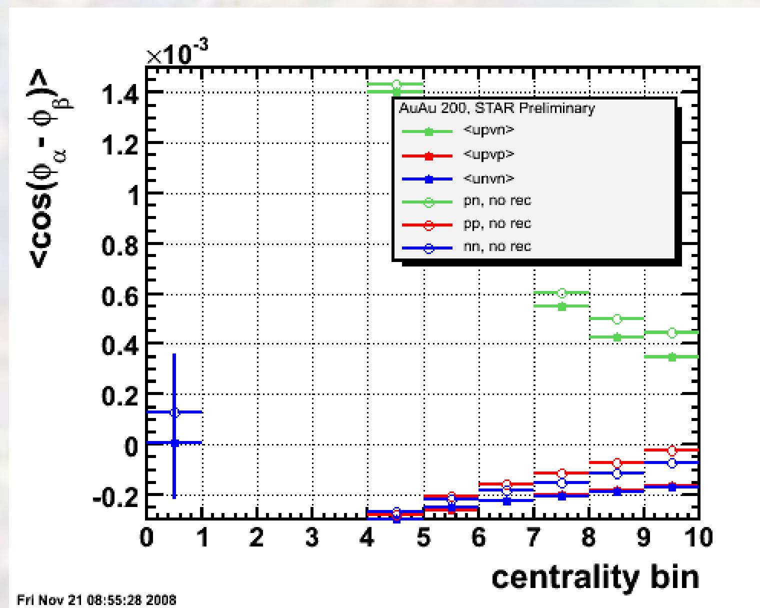
EXTRA SLIDES

Recentering, <cos(phi1-phi2)>

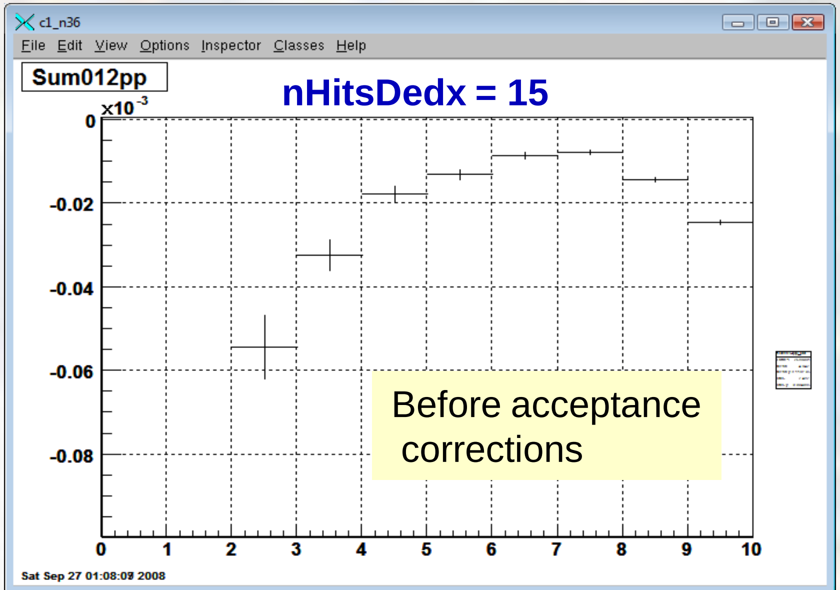








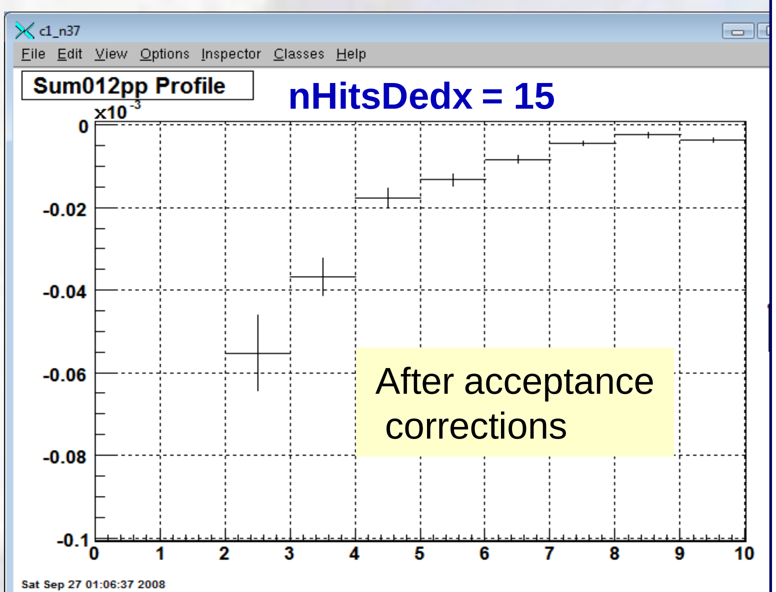
J. Thomas: Further testing acceptance corrections



Let us make acceptance worse!

(requiring large number of hits used for dEdx calculation significantly worsens the uniformity of acceptance)

How it works:



1.2 Acceptance effects. Cumulants and "recentering"

In order to remove acceptance effects in this study we use cumulant techniques. Then, introducing notations $u = e^{i\phi}$ and $v = e^{-i\phi}$, one has

$$\begin{aligned}
\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle &= \langle\Re\{u_\alpha u_\beta {v_c}^2\}\rangle = \langle\langle\Re\{u_\alpha u_\beta {v_c}^2\}\rangle\rangle + \\
&+\Re\{\langle\langle u_\alpha u_\beta\rangle\rangle\langle {v_c}^2\rangle\} + \Re\{\langle\langle u_\alpha {v_c}^2\rangle\rangle\langle u_\beta\rangle\} + \Re\{\langle\langle u_\beta {v_c}^2\rangle\rangle\langle u_\alpha\rangle\} + \\
&+\Re\{\langle u_\alpha\rangle\langle u_\beta\rangle\langle {v_c}^2\rangle\} = \langle\langle\Re\{u_\alpha u_\beta {v_c}^2\}\rangle\rangle + \qquad (1.10)\\
&+\Re\{\langle u_\alpha u_\beta\rangle\langle {v_c}^2\rangle\} + \Re\{\langle u_\alpha {v_c}^2\rangle\langle u_\beta\rangle\} + \Re\{\langle u_\beta {v_c}^2\rangle\langle u_\alpha\rangle\} + \\
&-2\Re\{\langle u_\alpha\rangle\langle u_\beta\rangle\langle {v_c}^2\rangle\} \qquad (1.11)
\end{aligned}$$

Note that in case of perfect acceptance, the cumulant $\langle\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle\rangle$ coincides with $\langle\cos(\phi_\alpha+\phi_\beta-2\phi_c)\rangle$.

Two comments in order:

- To account of acceptance effect is sufficient to perform "recentering" $u \to u - \langle u\rangle$, and
- performing "classical" calculation of cumulants subtracting corresponding terms, one has to calculate not only real but also imaginary parts of different correlators, e.g. accounting for

$$\Re\{\langle\langle u_\alpha u_\beta\rangle\rangle\langle {v_c}^2\rangle\} = \Re\{\langle\langle u_\alpha u_\beta\rangle\rangle\}\Re\{\langle {v_c}^2\rangle\} - \Im\{\langle\langle u_\alpha u_\beta\rangle\rangle\}\Im\{\langle {v_c}^2\rangle\}. \qquad (1.12)$$

Electron contamination? No.

CONCLUSIONS: it is not electrons...

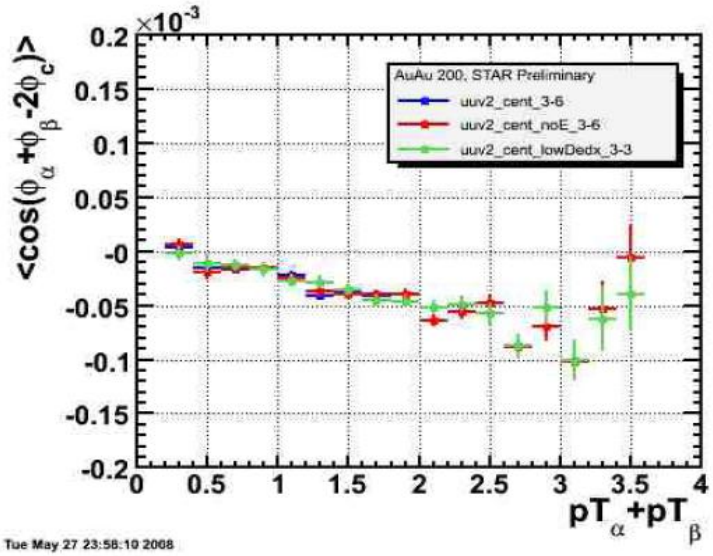


Figure 23: Transverse momentum dependence of the signal for no cut on Dedx, with cut to re electrons, and selecting lowDedx tracks.

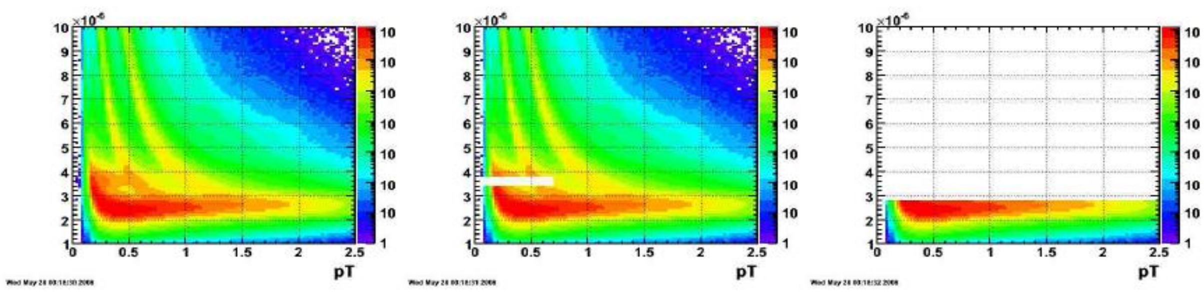
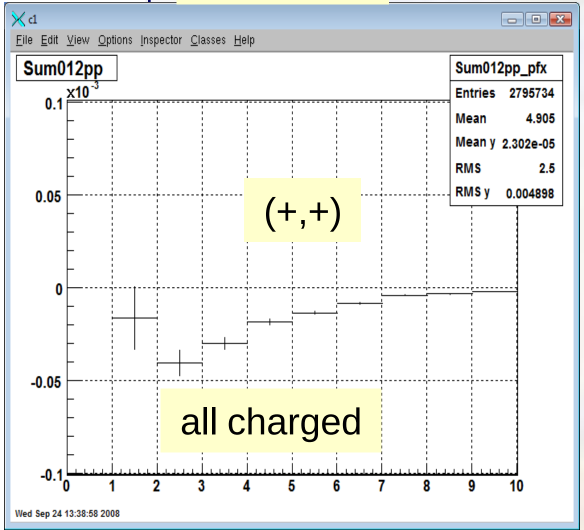
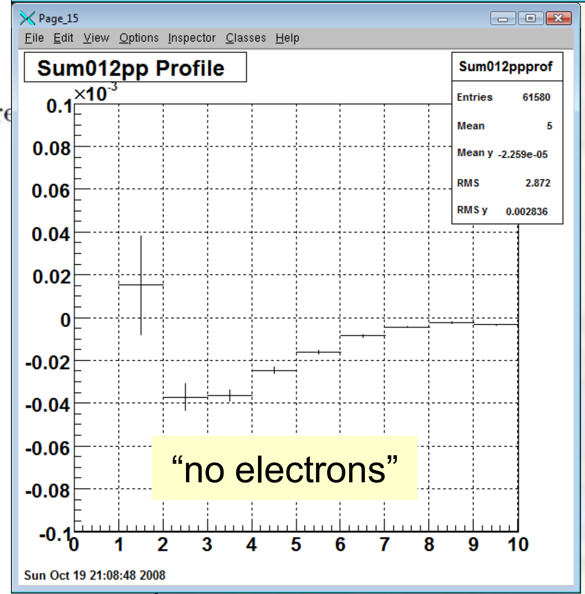


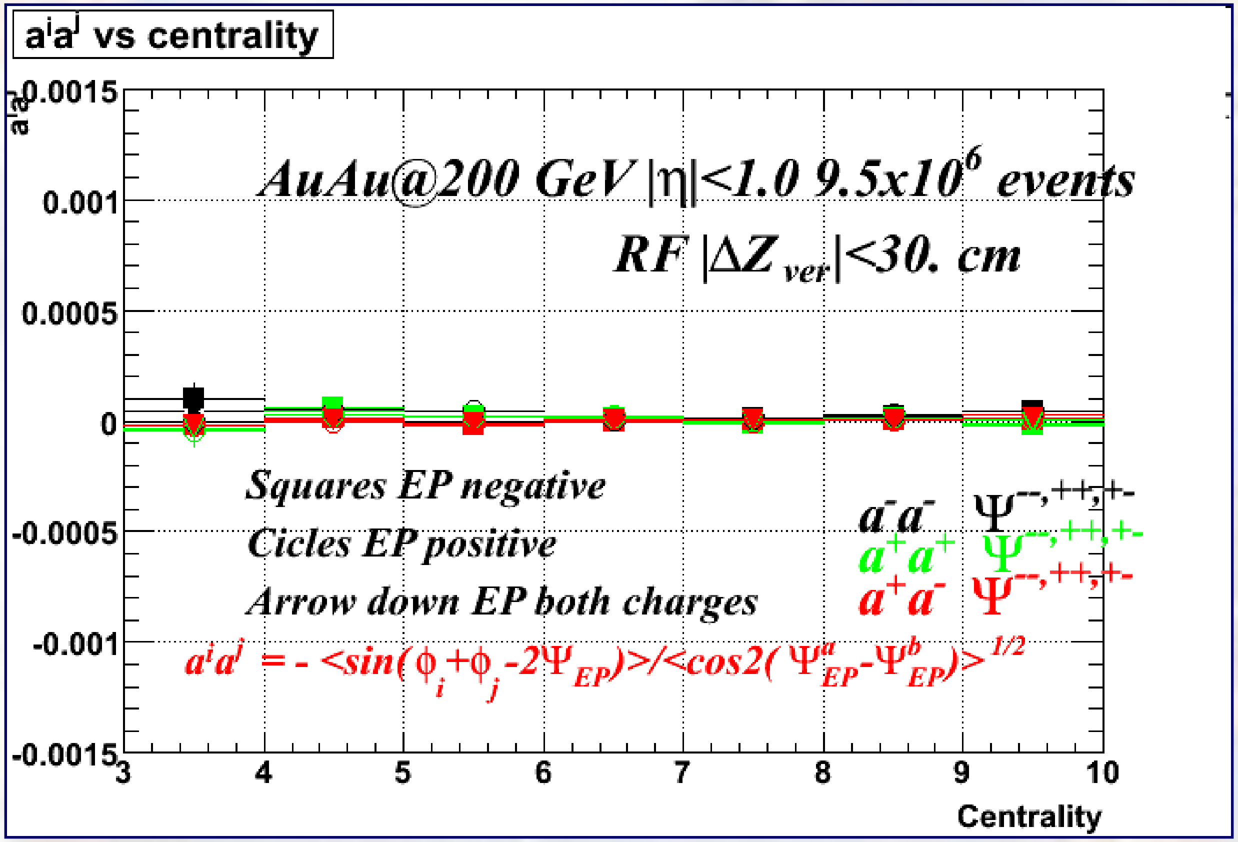
Figure 24: Dedx plots for three selections used in Fig. 23
. Left: original, middle: electron suppressed, right: selection of "low Dedx" tracks.

J. Thomas





Getting zero where it should be…



V. Dzhordzhadze:

Correlations wrt plane shifted by pi/4 relative to RP.

Background correlations

$$\left\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \right\rangle = -a_\alpha a_\beta + \text{[non } \mathcal{P}\text{-odd effects]}$$

1. "Flowing" resonance decays / RP dependent fragmentation

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle \approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle \, v_{2,res}}{N_{ch}} \, v_{2,c}$$

2. Global (hyperon) polarization – measured to be consistent with zero..

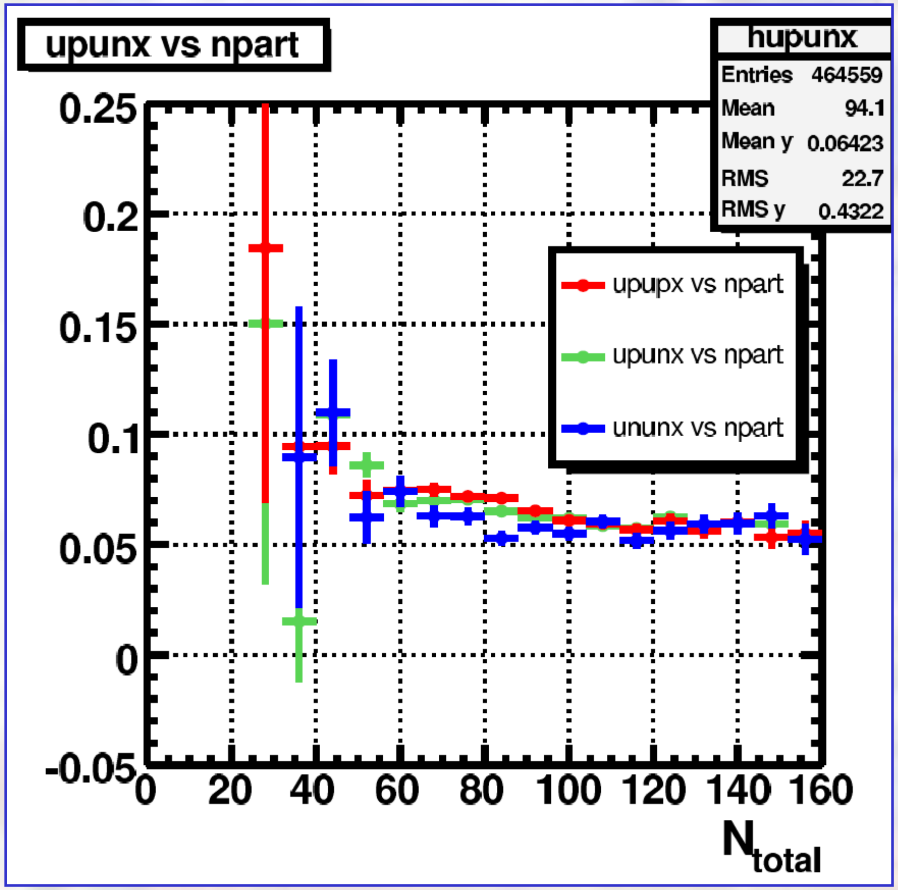
3. Directed flow fluctuations -- wrong sign contribution

4. Coulomb effects (under investigation)

…

5. Detector effects

"boosted" PYTHIA

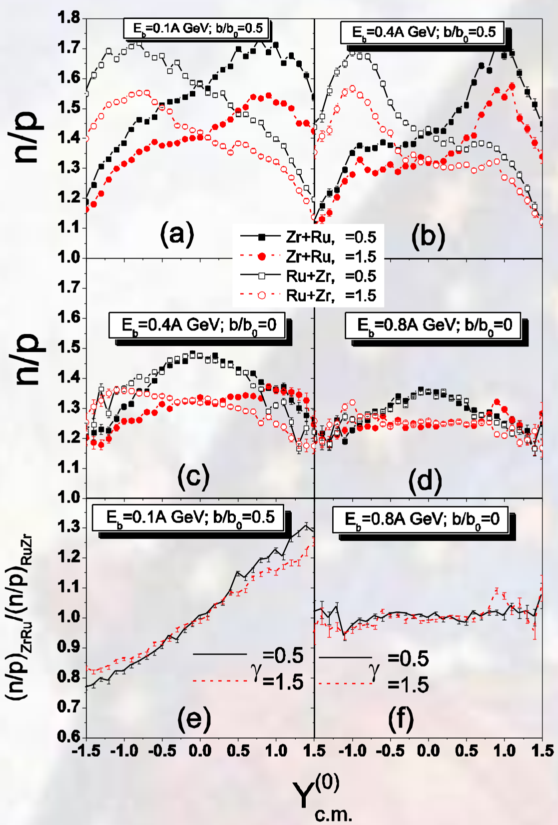


pp-collision boosted with

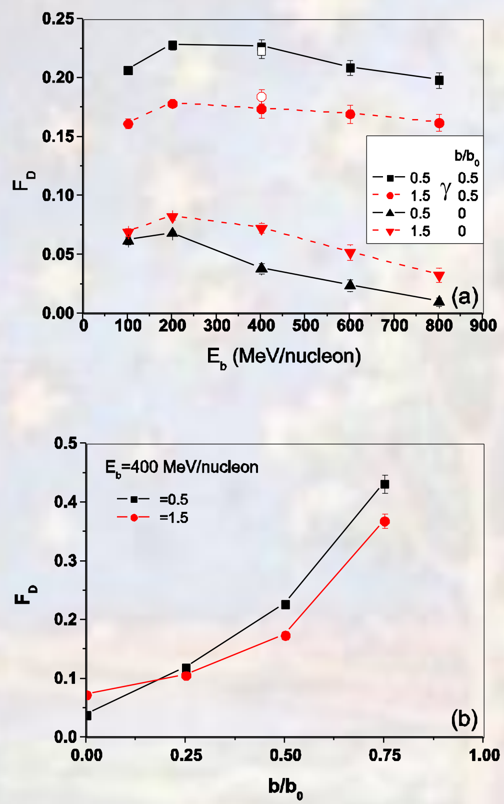
$$\boxed{v_r(\phi) = 0.4(1 + 2 \cdot 0.1\cos(2\phi))}$$

To compare with AA collisions one has to rescale the results with $1/N_{part}$

Nucleon double ratio from Ru/Zr+Zr/Ru



2006-PhysRevC_73_051601(R)



Advantage: to show simultaneously the dependence on symmetry energy and the degree of isospin equilibrium

The symmetry energy effect On F_D is enhanced when E_b~400A MeV, b/b_0~0.5

Others: **Bao-An Li et al.: (using Sn isotoptes)**

Double N/P ratio: Phys.Lett.B634:378-382,2006

Double pi-/pi+ ratios: Phys.Rev.C73:034603,2006

Double N-P differential flow : nucl-th/0606003